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Defining crash configurations for Powered Two-Wheelers: Comparing ISO 13232 to recent in-depth crash data from Germany, India and China

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ABSTRACT

The motorcyclist safety standard ISO 13232, based on crash data from Europe and the USA from the 1970s, still sets the direction for the development and evaluation of protective measures today. However, it is unclear how relevant the crash configurations in the standard are to present-day motorcycle crashes in Europe, the USA and other parts of the world. We analyzed recent in-depth crash data from Germany, India and China, examining powered two-wheeler (PTW) crash configurations in which at least one police-reported serious injury was present. After assessing the relevance of the ISO's PTW crash configurations to those we found in each country, we suggested new configurations to guide the development of safety systems that would be more effective at reducing PTW-related fatalities and serious injuries. In all three databases, passenger cars were among the top two most frequent collision partners and a car front impacting the side of the PTW was the most common configuration. Notably, although collisions with trucks constituted the most common scenario in India and ground impact (primary collision) was a common scenario in both Germany and India, the ISO did not include either configuration. Further, in three of the seven ISO crash configurations, one of the collision partners is stationary, although stationary collision partners were rare in our data. Our results show that the ISO crash configurations do not represent the most frequent PTW road crashes in Germany, India or China. However, the Chinese database was confined to crashes with a collision partner with four or more wheels. Further, weighting factors for these data were not available, so we could not extrapolate the frequency of the Chinese crash configurations across the entire population. A revised version of the ISO could serve as a basis for a full-scale PTW crash test program. However, the observed differences between countries imply that a single global standard may not be feasible. To optimize the evaluation of a PTW safety system, we recommend the inclusion of configurations which are frequent in the region or country of interest—in addition to common configurations occurring frequently all around the world.

1. Introduction

Globally, 28% of road traffic fatalities are riders of powered two-wheelers (PTWs) and three-wheelers (World Health Organization, 2018). Data from Asian countries show an even higher percentage of fatalities for these transportation modes: Thailand, 74%; Indonesia, 74%; Malaysia, 62%; the Philippines, 53%; India, 41%; and China, 27% (World Health Organization, 2018, 2015). These percentages translate to the following estimated numbers of fatalities per year (World Health Organization, 2018, 2015): 16,643 in Thailand, 23,447 in Indonesia, 4, 420 in Malaysia, 5,501 in the Philippines, 119,636 in India, and 70,569 in China. While PTW fatalities burden societies almost everywhere, the high percentages and absolute numbers of PTW fatalities in Southeast Asia, China, and India call for additional efforts to improve PTW safety. Therefore, additional research focusing on these regions is called for, with the aim to reduce PTW crashes and the risk of fatalities and serious injuries when these crashes occur.

Regulatory and consumer testing has helped improve passenger car safety over the years (Kullgren et al., 2019, 2010). In contrast, there is no full-scale regulatory safety testing or assessment program targeted at guiding PTW users, despite the existence of a standardized test procedure for assessing PTW safety (ISO 13232: see Van Driessche, 1994).

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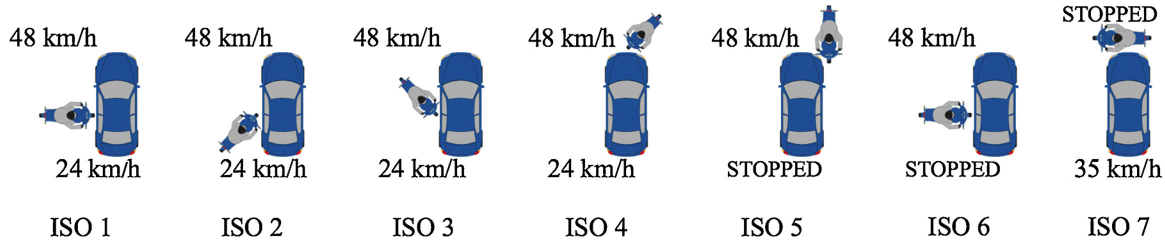


Fig. 1. The seven ISO 13232-recommended full-scale crash configurations (PTW speed on top and car speed at bottom).

The ISO standard defines seven crash configurations (also known as crash scenarios) between passenger cars (the only collision partner considered) and PTWs, illustrated in Fig. 1. The standard also specifies the motorcycle anthropometric test device to be used (a modified and helmeted Hybrid III 50th-percentile male dummy with specified instrumentation and injury assessment).

The ISO crash configurations were selected from 200 configurations derived from the analysis of 621 real-world crashes that occurred in Los Angeles, USA (Hurt et al., 1981) and Hannover, Germany (Otte, 1980). The travel speeds, collision angle (the relative angle between collision partners), and impact locations of each are specified since these three parameters influence crash kinematics and PTW rider injuries.

For the standard to be effective in reducing PTW injuries in a specific region, it should reflect the most frequent collision partners and crash configurations in that region. Three recent works support the ISO 13232 finding that passenger cars were the most frequent collision partners for PTWs in Europe (although the research focused on injuries rather than crash configurations): a comparative analysis of the Motorcycle Accidents In-Depth Study (MAIDS) database, which includes data from six large European countries and On The Spot (OTS) database from the United Kingdom found that passenger cars were the most frequent collision partners for PTW in both database (Mccarthy et al., 2017); a paper by Aarts et al. (2016), which found that the most frequent collision partners of severely injured motorcyclists were passenger cars, followed by fixed-object and single-PTW crashes (either PTW-fixed object collision or PTW falling on the ground); and a detailed analysis of German crash data by Otte et al. (2015), which confirmed that passenger cars and fixed objects were the dominating collision partners of PTWs.

Many studies have identified important crash scenarios in various countries. For example, Otte et al. (2015) identified five crash configurations that were not included in the ISO standard. In the German In-Depth Accident Database (GIDAS), one of the most common fatal PTW crash scenarios was that of PTW riders losing control (Fredriksson and Sui, 2015). This crash configuration was not included in the ISO standard. Grassi et al. (2018) suggested seven crash configurations to represent the most common PTW crashes in Europe, but only one of these was similar to a configuration detailed in the ISO standard. A study analyzing crash data collected in Lyon and Marseille, France, which found that head-on side collisions were the most frequent car-to-PTW collisions, made a recommendation: "head-on-side/oblique-on-side and head-on crash configurations must be considered to support the design and evaluation of safety devices" (Cherta Ballester et al., 2019). Out of the three crash configurations recommended, the head-on crash configuration was the only one not included in the ISO standard. Further, the European project "Protective Innovations of New Equipment for Enhanced Rider Safety" (PIONEERS), which investigated recent PTW crashes in multiple European countries, found that those crashes were different from those detailed in the ISO 13232 standard (Mensa et al., 2020).

Unfortunately, research focusing on PTW crashes in Southeast Asia, China and India is sparse, even though these regions account for the greatest number of PTW fatalities and severe injuries globally. The following are the most significant findings from the studies that do exist. In India, head-on collisions in longitudinal traffic were the most frequent scenario, both for fatal crashes on a specific highway stretch (Naqvi and Tiwari, 2017) and for injury crashes recorded in the more nationally representative Road Safety Sampling System India (RASSI) database (Lich et al., 2015). Upon analyzing insurance data from Thailand, Carmai et al. (2018) found that the most frequent crash types were PTW riders being sideswiped and PTW riders losing control. Both sideswipe and PTW riders losing control were not included in the ISO standard. In contrast, studies using data from Europe, the USA and India found that sideswipes were not frequent. As PTWs are typically designed for a global market, the ISO 13232 should preferably include crash configurations that are common around the world. If further research shows that sideswiping (or other configurations not common in Europe) frequently occurs in other countries, then perhaps this configuration should be represented in the global safety standards.

Much of the previous research on PTW safety was carried out on data from Europe and the USA, where the type of PTW, traffic infrastructure, and PTW usage are vastly different from those in countries like India, China, and Southeast Asia. Further, most studies were carried out on data with a limited sample or on crashes from decades ago. In fact, in-depth crash data from India and China did not exist when the ISO 13232 was created in 1996. Further, significant changes in safety regulations and road traffic infrastructure have been introduced over the last three decades, which can influence conflicts between road users. The ISO standard, created using data from the 1970s, does not reflect these changes. Therefore, studies using large crash data samples from several regions of the world are necessary to determine representative crash configurations that can be used to update the ISO standard.

This study aims to identify the most frequent PTW crash configurations in Germany, India and China using the most recent information available and compare them with those detailed in the ISO 13232. These configurations can then be used to guide the design of test programs of PTW safety, with the long-term goal of reducing the fatalities and injuries of riders in PTW crashes in these three countries.

2. Method

We used the GIDAS, RASSI, and China In-Depth Accident Study (CIDAS) databases. These countries were selected based on their economic development. Germany has the highest GDP and lowest per-capita traffic fatality rate of the three countries, while India has the lowest GDP and highest traffic fatality rate; China is somewhere between the two. Studying and comparing data from these three countries might also provide an opportunity to estimate future changes in the crash

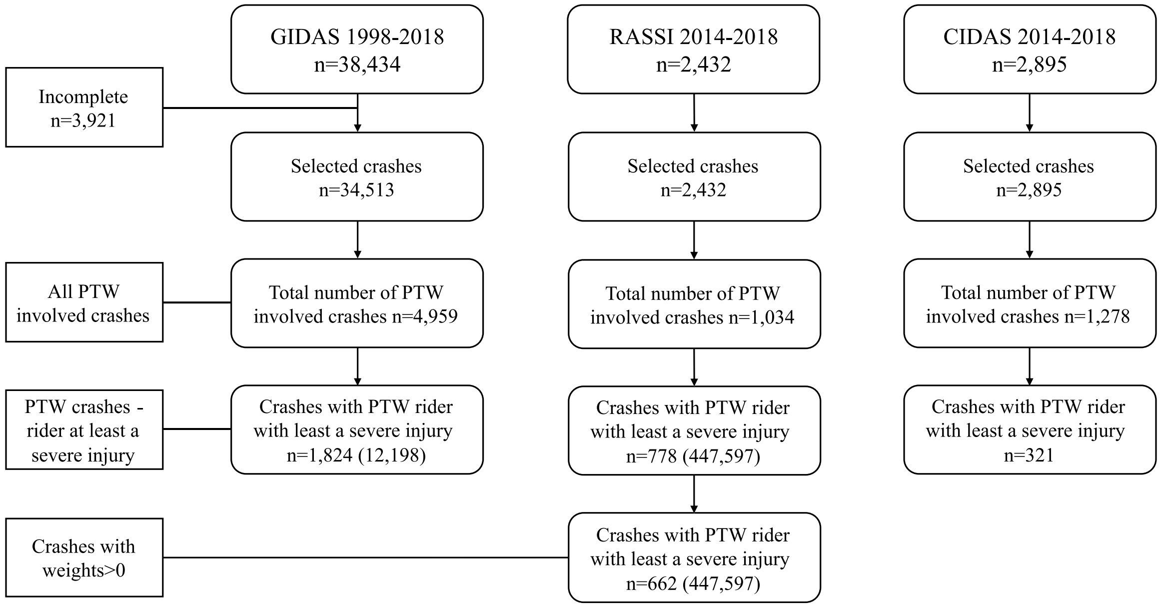


Fig. 2. Database filtering summary (weighted numbers). Note: Crashes with weights less than zero were present only in RASSI database.

populations, since as a country's economy develops its transportation patterns also change. One can consider that India might continue to develop, acquiring the crash configurations seen today in China and, eventually, both countries might acquire those seen today in Germany. Therefore, a comparison of the selected databases may indicate future changes in the most frequent PTW crash configurations in India and China.

Below, each database is described, along with the filtering performed to extract the relevant data. In addition, where possible the data were weighted to render them representative of the population of the respective country. These three in-depth crash databases include information such as scene details, road condition, and location, along with vehicle-level information such as vehicle make and model, exterior information, availability of safety features, damage to the vehicle, and travel and travel speeds. Information related to the occupants or rider, like seating position, restraint usage, injuries sustained, and demographics are also provided.

For this study we considered both light two-wheeled vehicles and motorcycles, respectively classified as L1e (maximum design speed not over 45 km/h and engine capacity up to 50 cm^3) and L3e (maximum design speed over 45 km/h and engine capacity more than 50 cm^3), according to European Commission directives (European Commision, 2002). Powered bicycles and PTW variants with an additional wheel or attachment such as a sidecar were excluded from the study.

To identify the most frequent collision partners in events with more than one, we considered both the first collision partner and the one involved in the most severe collision for PTW (if they were different).

2.1. GIDAS data

The GIDAS database collects data from road crashes that occur in Dresden, Hannover, and surrounding rural areas. It includes crashes with at least one person who suffered from a suspected injury (Otte et al., 2003). Data from 1999 to 2018 were included in the analysis. Completely reconstructed cases (N = 34,513) were filtered from all cases in the GIDAS database (N = 38,434). There were 4,959 crashes involving PTWs. As there was more than one PTW involved in a few of the crashes, a total of 5,053 PTWs were included. Further, only crashes involving riders with serious or fatal injuries were extracted (N = 1,824 in which 117 riders sustained fatal injuries). Fig. 2 summarizes the filtering process.

2.1.1. Data processing – most frequent collision partners and impact conditions

Initially, seriously injured PTW riders were identified by merging crash injury data. Then, the most frequent collision partners and general characteristics such as precipitation, helmet usage, class and type of PTW were extracted. If the general area of damage (GAD) ["*VDI2*"] on the vehicle was the front, it was coded as "front"; if it was either the left or right side it was coded as "left" or "right". Frequency distributions were evaluated for these categories: travel speeds ["*V0*"] of car and PTW, collision angle ["*KWINK*"], and specific horizontal location of damage ["*VDI3*"] on the vehicle.

We made the included GIDAS data representative of Germany as a whole by weighting them at the crash level, using German national data about vehicle involvement and injury severity (Federal Statistical Office (Destatis), 2017). This method is widely used (Rosén and Sander, 2009). A more detailed explanation of weighting is given in Appendix A.

2.2. RASSI

RASSI is an in-depth crash database like GIDAS, but with parameters designed to reflect configurations and conditions (e.g., contributing factors, body types, and road types) specific to India. RASSI has the following inclusion criteria (Rameshkrishnan et al., 2013):

- The crash needs to occur on a public road within one of the data collection areas (Coimbatore, Pune, Ahmedabad, Kolkata, and Jaipur), and it must involve at least one motorized vehicle.

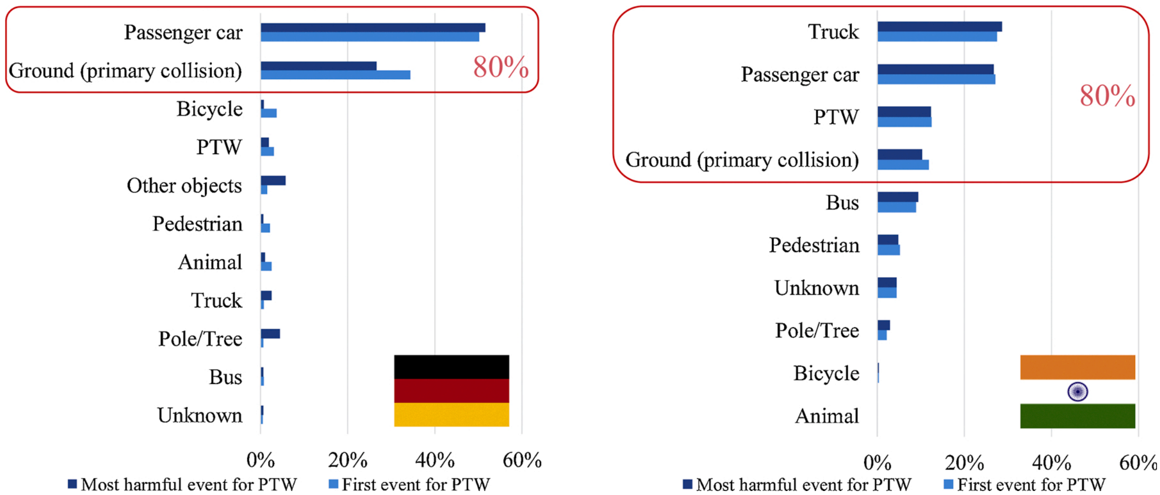


Fig. 3. Weighted distribution of PTW collision partner in crashes with at least one seriously injured PTW rider (left: GIDAS, right: RASSI.).

- The crash spot must be identifiable by: known final vehicle resting positions (photographs, etc.), vehicle trajectories (skid or brake marks, etc.), or other evidence (debris, damaged fixed objects, eyewitness, etc.).
- Measurements of the road, skid marks and other marks must be possible to collect.
- Vehicles must be available for inspection, to facilitate collection of data such as direct damage details, crush profile, intrusions, contacts, and safety system use.
- Make and model of each vehicle involved in the crash should be known.

2.2.1. *Data processing – most frequent collision partners and impact conditions*

For this study, RASSI data from January 2014 to April 2018 were used (N = 2,432). The filtering criteria were the same as in the GIDAS analysis, resulting in 778 crashes with at least one PTW involved and at least one serious injury to the rider (Fig. 2). Similar to GIDAS, frequency distributions were evaluated for these categories: GAD [*"GADEV1"*], travel speeds [*"V0_1ST"*] of involved vehicles, collision angle [*"COLLANGLE_1ST"*] distributions, and specific horizontal location of damage [*"SHL"*]. To make RASSI data representative of Indian data at the national level, the weighting factors provided in the database [*"INDIA-WEIGHT"*] were used.

2.3. *CIDAS*

The CIDAS database includes data from crashes in which at least one person was injured and one of the collision partners was a vehicle with four wheels or more, occurring in one of the following six cities (covering urban and rural areas in China): Changchun, Beijing, Weihai, Ningbo, Foshan, and Chengdu (Chen et al., 2014). The database does not include single-PTW crashes, such as collisions with objects or non-collision events in which the rider lost control and fell (hereafter referred to as ground-impact (primary collision) events). In this study, the CIDAS database was queried for PTW crashes with at least one police-reported serious injury from 2014 to 2018 (N = 321; see Fig. 2).

2.3.1. *Data processing – most frequent collision partners and impact conditions*

For the analysis, we employed a filtering process similar to that used for the analysis of GIDAS data. However, there were no weighting factors readily available and there were no detailed national statistics on road crashes available at the time of this study. Hence, it is not known how accurately the CIDAS data represent PTW crashes across China.

3. Results

Results are divided into two sections for simplicity. Since CIDAS does not include single PTW crashes or crashes with pedestrians or vehicles with less than four wheels, only the weighted RASSI and GIDAS data are presented in Section 3.1. In Section 3.2, we added CIDAS data to a corresponding subset of the GIDAS and RASSI data while analyzing collision partners and crash configurations. Conducting separate analyses ensured that equivalent data were being compared.

3.1. *Serious injury crashes involving PTWs (Germany and India)*

Most of the PTW crashes occurred in bright daylight, without adverse weather or road surface conditions (Germany 82%; India 98%). Further, most crashes occurred in urban areas (Germany 81% urban, 19% rural; India 65% urban, 35% rural). Less than 10% of the PTWs were fitted with an anti-lock braking system (ABS). The types of PTWs were different in Germany and India. PTWs with an engine capacity of less than 125 cm^3 were most common in India (74%), while in Germany, 50% of the involved PTWs had engines at least that large. Only 16% of the PTW riders in India used helmets, while in Germany 76% were helmeted. Most PTW riders were male (Germany 91%; India 81%). In both countries, the average injured PTW rider's height and weight were close to those of a Hybrid III 50th percentile average male anthropometric test device.

Collision partners must be considered in order to derive crash configurations and develop effective countermeasures. As noted, we analyzed the collision partner in events with more than one, we considered both the first collision partner and the one involved in the most severe collision for the PTW (if they were different). There was no change in the ranking of collision partners in both countries, whether

Table 1
Crash configuration cross-plot. Background shade indicate low (light) to high (dark) percentages of general area of damage (GAD) combinations: (na indicates "not available"). Numbers in bold highlight the most frequent combinations.

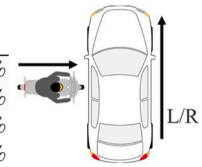
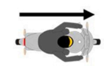
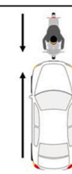
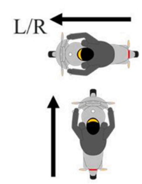
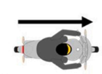
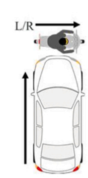
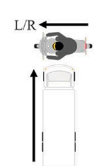
Database	GAD distribution						Most frequent crash configuration	Name
GIDAS		GAD of Car						
	GAD of PTW	front	left	right	back	na		CS 1
	front	15.5%	**16.9%**	**13.9%**	11.4%	0.1%		
	left	7.6%	1.6%	4.9%	0.4%	0.1%		
	right	8.4%	6.8%	0.9%	3.1%	0.0%		
	back	3.4%	0.0%	0.6%	0.0%	0.0%		
	na	1.6%	1.7%	0.7%	0.2%	0.1%		
		GAD of Ground						
	GAD of PTW	Not applicable					 Ground Impact	CS 2
	front	9.4%						
	left	16.8%						
	right	17.3%						
	rear	0.8%						
	na	**55.4%**						
RASSI		GAD of Truck						
	GAD of PTW	front	left	right	back	na		CS 3
	front	**21.5%**	5.3%	7.5%	10.4%	0.0%		
	left	7.6%	0.4%	8.8%	1.0%	0.0%		
	right	5.6%	11.5%	11.0%	0.0%	0.0%		
	back	7.9%	0.9%	0.6%	0.0%	0.0%		
	na	0.0%	0.0%	0.0%	0.0%	0.0%		
		GAD of Car						
	GAD of PTW	front	left	right	back	na		CS 4
	front	**41.0%**	2.5%	2.6%	1.2%	0.0%		
	left	15.2%	0.8%	1.1%	0.0%	0.0%		
	right	18.9%	2.5%	6.5%	0.0%	0.0%		
	back	7.7%	0.0%	0.0%	0.0%	0.0%		
	na	0.0%	0.0%	0.0%	0.0%	0.0%		
		GAD of PTW (Collision partner)						
	GAD of PTW	front	left	right	back	na		CS 5
	front	25.5%	7.4%	9.4%	3.6%	0.0%		
	left	**10.3%**	5.3%	2.5%	0.0%	0.0%		
	right	**19.5%**	3.8%	7.4%	0.0%	0.0%		
	back	5.2%	0.0%	0.0%	0.0%	0.0%		
	na	0.0%	0.0%	0.0%	0.0%	0.0%		
		GAD of Ground						
	GAD of PTW	Not applicable					 Ground Impact	CS 6
	front	0.4%						
	left	41.6%						
	right	**55.0%**						
	back	0.0%						
	na	3.0%						
CIDAS		GAD of Car						
	GAD of PTW	front	left	right	back	na		CS 7
	front	4.4%	5.5%	6.6%	1.1%	2.2%		
	left	**20.8%**	1.6%	6.0%	0.0%	2.7%		
	right	**24.0%**	7.7%	1.6%	1.1%	1.1%		
	back	8.2%	0.0%	0.5%	0.0%	0.0%		
	na	1.1%	1.6%	1.6%	0.0%	0.5%		
		GAD of Truck						
	GAD of PTW	front	left	right	back	na		CS 8
	front	9.1%	7.8%	5.2%	2.6%	1.3%		
	left	**32.5%**	1.3%	16.9%	0.0%	0.0%		
	right	**9.1%**	3.9%	0.0%	1.3%	1.3%		
	back	6.5%	0.0%	0.0%	0.0%	0.0%		
	na	1.3%	0.0%	0.0%	0.0%	0.0%		

Table 2
Vehicle travel speeds in km/h (covering 60% of crashes in each configuration).

Crash configuration	Travel speed of PTW	Travel speed of collision partner
CS 1 (GIDAS)	50	20
CS 2 (GIDAS)	60	Not applicable (ground impact)
CS 3 (RASSI)	35	35
CS 4 (RASSI)	35	55
CS 5 (RASSI)	48	25
CS 6 (RASSI)	38	Not applicable (ground impact)
CS 7 (CIDAS)	30	55
CS 8 (CIDAS)	25	45

they were ranked by first or by most harmful event (Fig. 3). In both countries, passenger cars were among the most frequent collision partners: in Germany, half of the PTWs collided with a passenger car, while in India the figure was only 25%. A truck, the most common collision partner in India, was an uncommon one in Germany. In Germany, the second most common crash configuration (approximately 25%) was ground impact (primary collision). In India, ground impact (primary collision) events were not as common (10%).

3.2. Most common crash configurations

We extracted detailed information about crash configurations only for the most frequent collision partners from the three databases. Recall that CIDAS is unweighted, and only includes crashes with motor vehicles with four or more wheels. Since more than 50% of the PTW crashes in GIDAS and RASSI involved vehicles with four or more wheels, we decided to include CIDAS data for further analysis and comparison. Analysis of the CIDAS data revealed that passenger cars (68%) and trucks (27%) were the most frequent collision partners for PTWs. In Table 1, the eight most frequent crash configurations from the three databases are described and prioritized by cross-plotting the general area of damage (GAD) of both participants in the first collision.

In GIDAS, the most frequent PTW-car crash configuration was PTW front impacting car left, followed by PTW front impacting car front. For a PTW rider, impacting the left or right side of a vehicle makes little difference, so these two configurations were combined into one. Therefore, the most frequent crash configuration in GIDAS for PTW-car collisions is PTW impacting the side of a car (see pictogram in Row 1 of Table 1). For the second most common scenario, ground impact (primary collision), information about the PTW damage area was not available (na) in more than 50% of the cases. In India, head-on collisions between PTWs and trucks or passenger cars were the most frequent configuration. However, when the two configurations in which the PTW front collided with the side of a vehicle were combined (as with GIDAS data), this scenario became the most frequent, followed by head-on collision. In the ground impacts (primary collision), the PTWs had damage on the left or right side. In CIDAS, the most frequent crash configuration was car or truck front impacting left or right side of the PTW.

To fully specify crash configurations, travel speeds of collision partners are needed. In order to identify the travel speeds, we plotted cumulative distributions of both vehicles' travel speeds in the most frequent crash configurations (Appendix B) and chose a travel speed which covers 60% of the crashes with that crash configuration for that region (Table 2). The travel speeds of PTWs were higher in GIDAS compared to those in RASSI and CIDAS, which can be explained by the higher-capacity engines and better infrastructure in Germany. The opposite was true for the speeds of collision partners: GIDAS recorded lower speeds than RASSI and CIDAS.

Crash kinematics and PTW rider injury depend on collision partner, impact locations, and collision angle. Hence, we include these details (where available) for our crash configuration descriptions in Table 3. Note that collision angle and impact location are meaningless for single PTW or ground impact (primary collision) configurations.

In CS 1, the most frequent type of crash in Germany, the PTW frontal impacts were spread over the side of the car, with one-third impacting near the front wheel. The most frequent crash configurations in RASSI were CSs 3 and 4, head-on collisions with truck and passenger car. Most of these impacts occurred at the right side of the front for both trucks (81%) and passenger cars (62%), and the impact angles were mostly within 15° of the direction of travel of the truck or car. The travel speeds of passenger cars were higher than those of trucks collision angle. This crash configuration might be the consequence of misjudgment while overtaking on an undivided road.

In CS 5 (PTW front impacting side of another PTW), impact locations were unknown, and for a significant proportion of the crashes the collision angles were approximately 90°. This crash configuration might result from an inattentive rider in an intersection. In CSs 7 and 8, no impact location stood out, and collision angles were unknown for approximately one-fourth of the crashes. The sideswipe configuration (ISO 5) was not frequently observed in any of the three databases.

One of the major findings of this study is that there were several crash configurations (CSs 2, 3, 5, 6, and 8) that were not covered in ISO 13232 (Table 4). In fact, head-on collisions (CSs 3 and 4) and ground impacts (primary collision) (CSs 2 and 6), were among the most frequent in our analyses. Other notable differences are that the travel speeds were slightly higher than in ISO 13232 for the majority of the common crash scenarios, and ISO 13232 contains crash configurations with one stationary collision partner, which were sparse in our analysis.

There were few crash configurations common across all three databases, and they were not the most frequent ones. Car front impacting the side of a PTW was the most frequent configuration common to all three, accounting for 16% of all PTW-car crashes in GIDAS (weighted to Germany), 34% in RASSI (weighted to India, and 45% in CIDAS (unweighted). Head-on collisions accounted for 16% and 41% in Germany and India, respectively, while in CIDAS they accounted for only 5%. PTW front impacting side of car accounted for 31% in Germany, 5% in India and 12% in CIDAS.

4. Discussion

In this study, we analyzed crashes with at least one seriously injured PTW rider, using data from Germany, India and China (recall that the data from China only included crashes with vehicles with four or more wheels). The eight most common crash scenarios were then compared to the seven configurations described in the ISO 13232, in order to

Table 3
Distribution of impact location and collision angle in the most frequent crash configurations.

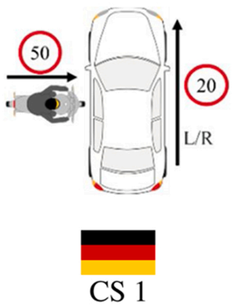
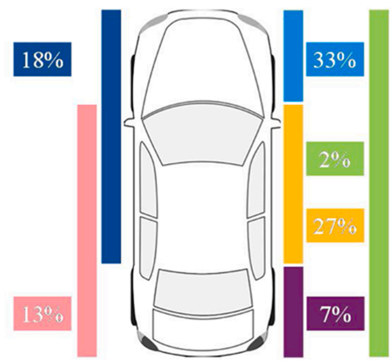
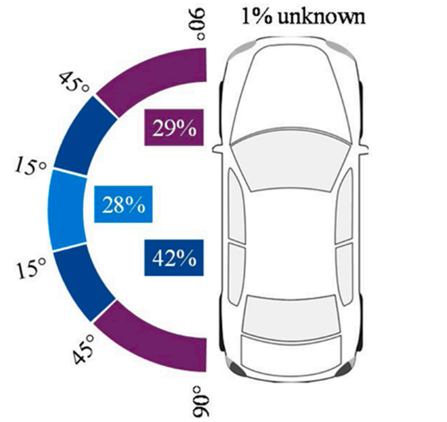
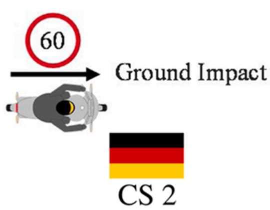
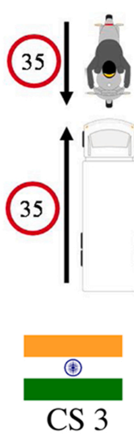
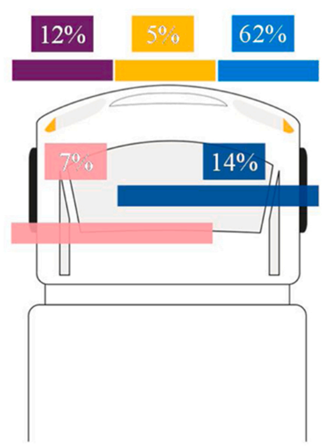
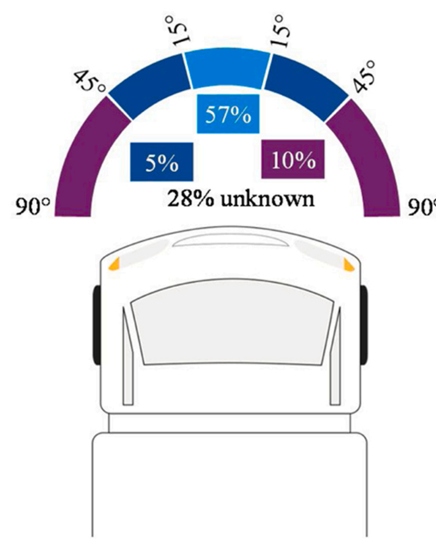
Most Frequent crash configuration	Distribution of impact location on the collision partner	Collision angle distribution (relative angle between collision partners)
		
	Not applicable	Not applicable
		

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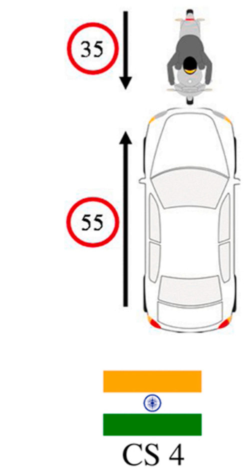
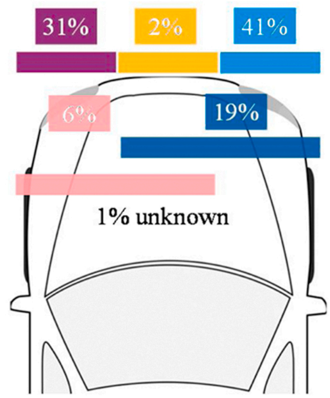
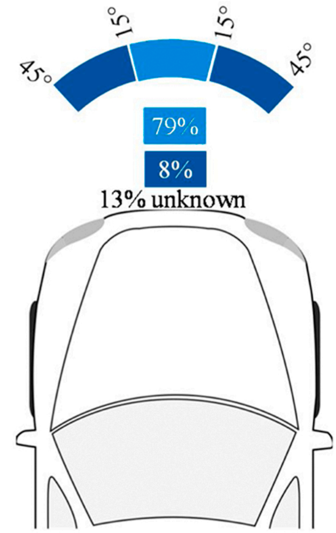
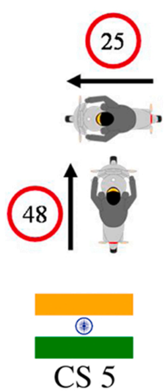
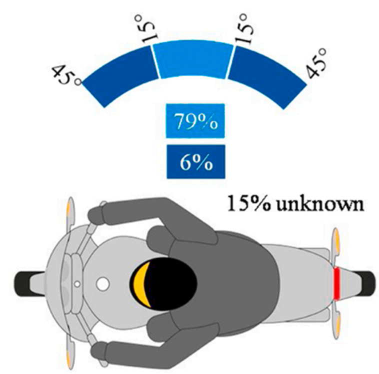
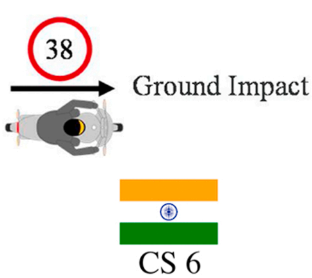
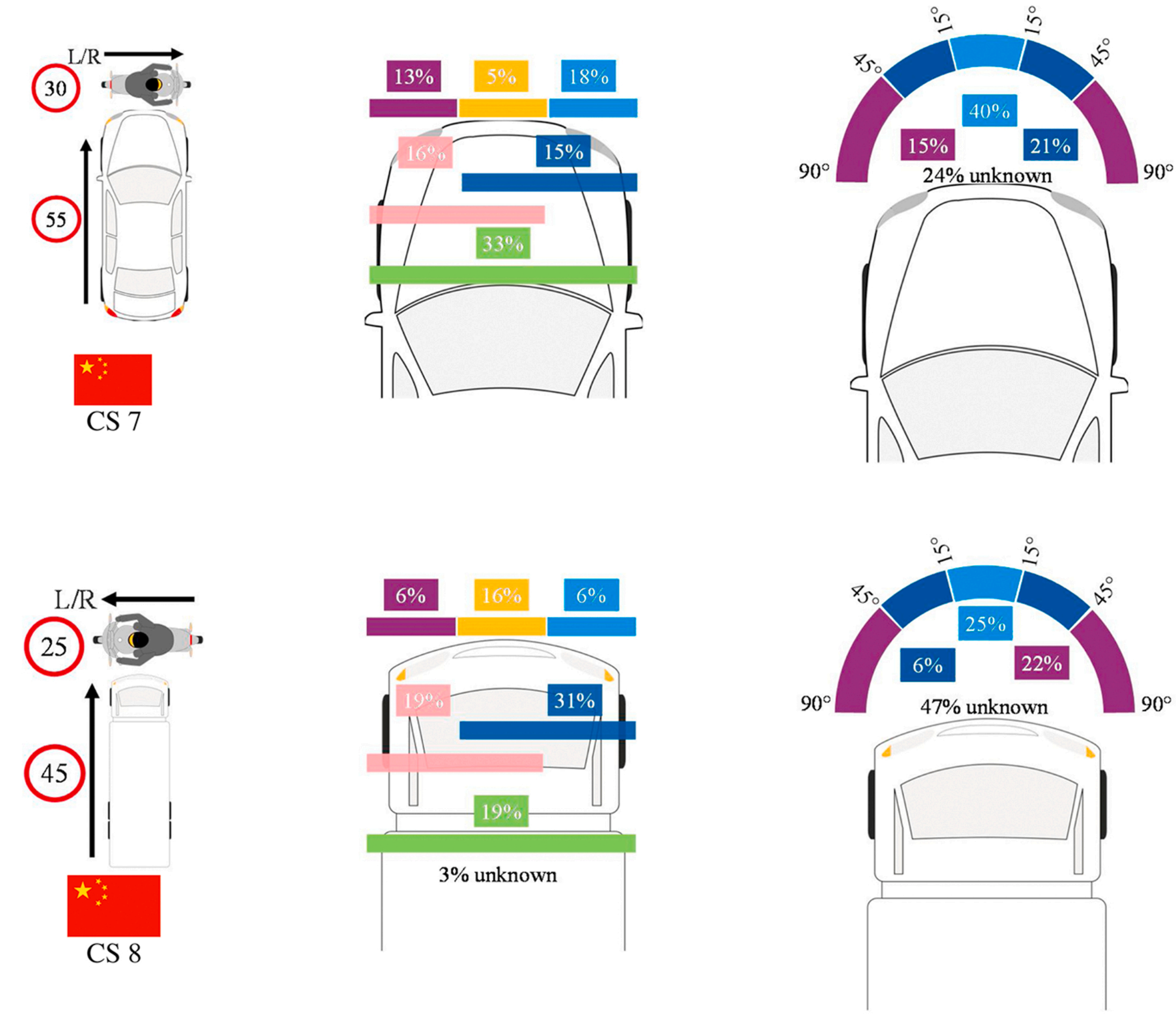
Table 3 (*continued*)

		
	Impact locations not available for PTW	
	Not applicable	Not applicable

(*continued on next page*)

Table 3 (*continued*)



investigate the standard's current relevance for these three countries.

Some differences can be explained by driver behavior, the PTW's primary use, economic differences, PTW engine size, and road infrastructure. In high-income countries like Germany, PTW use is primarily recreational (Lin and Kraus, 2009), while the PTW is often used for daily commuting or delivering goods in India, as in many low- and middle-income countries. This difference is evident from the common types of PTWs in use: in Germany (as noted), approximately 50% of involved PTWs had engine volume more than 125 cm^3, and their travel speeds were marginally higher than in India and CIDAS.

Even with lower travel speeds, the proportion of fatal PTW crashes was significantly higher in India than in Germany. The difference in crash fatality rates can be correlated to the much higher helmet usage rate in Germany. Since helmets are effective in preventing fatalities (Fernandes and Alves de Sousa, 2013), increasing helmet usage in India would likely substantially reduce PTW rider fatalities.

The scope of ISO 13232 included only a specific type of collision partner, the passenger car (Van Driessche, 1994). The drawback of restricting collision partner to only passenger cars were evident in many follow-up studies of the ISO standard (Grassi et al., 2018; Mensa et al., 2020). We found that, in Germany, the passenger car is still the PTW's most frequent collision partner, which confirms previous research (Fredriksson and Sui, 2015; Otte et al., 2015). Thus, in Germany's case the ISO standard seems to still be relevant. Further, this finding is in line with a recent European study on serious road traffic crashes, which reported that passenger cars were the most common collision partners (42% to 59%) for seriously injured PTW riders (Aarts et al., 2016). However, in India, we found trucks to be the PTW's most frequent collision partner; hence the ISO standard might not be as relevant there. Further, in other countries or regions where PTW-passenger car collisions are not the most common, it is likely that considering a passenger car as the only collision partner is not helpful. Ground impact (primary

Table 4

Comparison of crash configurations identified in this study (CSs 1–8) with those in ISO 13232 (ISOs 1–7). Letters indicate correspondence (P: Collison partner matching, A: Collision angle matching, S: Travel speeds comparable); empty cells indicate no correspondence.

	ISO 1	ISO 2	ISO 3	ISO 4	ISO 5	ISO 6	ISO 7
CS 1	PAS	PA	PA				
CS 2							
CS 3							
CS 4				P	PA		
CS 5							
CS 6							
CS 7							PA
CS 8							

collision) is another frequent configuration that the ISO standard does not include.

A recent study of the MAIDS database defined a set of seven crash configurations and found that only one was common to the ISO standard (Grassi et al., 2018). Their study includes crashes that occurred recently, with only one type of collision partner, a passenger car. Since the results did not include single PTW crashes and collision partners other than passenger cars, clearly the results are not representative of all PTW crashes. Most recently, the PIONEERS project also followed the ISO procedure—that is, excluding single PTW crashes and PTW crashes with collision partners other than passenger cars (Mensa et al., 2020). This methodology might provide useful results for regions where the number of passenger cars on the road is significantly higher than the number of other road users.

Looking at the specific crash configurations across the three countries showed that the proportion of head-on crashes involving PTWs was highest in India and lowest in China. This finding might be due to various differences between India and China such as road infrastructure, people's attitudes towards safety, and traffic laws and the strictness of their implementation. In fact, previous research by Naqvi and Tiwari, who found that the relative frequency of head-on collisions decreases on divided roads (Lich et al., 2015; Naqvi and Tiwari, 2017), suggests that having more divided roads with raised median barriers might be beneficial for reducing head-on collisions in India.

Another crash configuration that stood out in CIDAS and RASSI was the truck side colliding with the side of a PTW (a sideswipe collision). This scenario, which could occur when either vehicle was changing lanes or turning, would be at least partly prevented by improving the conspicuity of the PTW rider and expanding the truck driver's field of view. Investigations of fatal crashes on Indian highways reveal that most sideswipe collisions involving PTWs occurred at intersections or at median openings on divided roads (Naqvi and Tiwari, 2017). It would be challenging to create a representative test method that successfully replicates a sideswipe crash including the truck driver's field of view which is highly variable.

4.1. Limitations

The three databases have different inclusion criteria, so their results may not be directly comparable. However, weighting the RASSI and GIDAS results rendered them representative of their respective countries, and also makes the results comparable. There are many reasons to believe that crashes in India are actually under-reported, due to various issues in data collection and aggregation (Bhalla et al., 2017; Singh et al., 2018). However, weighting the RASSI data compensates for the under-reporting.

Another drawback of our study was the lack of even a minimum of details on crash data at a national level for China. On the other hand, it can be seen as a strength of this study that the data were weighted at the national level for Germany and India, an undertaking which was not attempted for the development of ISO 13232. Further, due to the filtering criteria of CIDAS, the data did not include single PTW crashes or PTW-PTW crashes.

For simplicity, this study considered only the PTW rider. This focus is a limitation, as there are crashes in which the rider does not suffer a serious injury, but the pillion rider suffers a serious or fatal injury.

Several studies have examined PTW injuries using accident data in the past. Ding et al., 2019 estimated relationship between speed and injury severity in terms of Abbreviated Injury Scale (AIS) levels of helmeted PTW rider based on GIDAS data. Others have studied factors, such as collision partners and crash configurations, which influence the injury levels of motorcyclists involved in crashes in China (Chang et al., 2019) and United Kingdom (Pai and Saleh, 2007). The latter study used only two categories (killed or serious injury), instead of the AIS categories in Ding et al.'s study on GIDAS data. Police-reported injury severity is less accurate than AIS severity. To select severe crashes, we used the criteria "at least a police-reported serious injury" instead of AIS levels, because in RASSI and CIDAS there were crashes with missing AIS codes that were reported as serious injuries. If AIS injury severity level had been used as the filtering criteria, these crashes would have been filtered out, resulting in a reduced sample size—which could affect the results.

This study used travel speed, rather than the speed just before the crash, to characterize crash configurations. As with injury severity, this simplification was made to avoid case reductions due to missing data. However, it should be noted that using travel speed instead of impact speed marginally overestimates the speed at the time of impact.

4.2. Future work

This study determined most frequent crash configurations that resulted in a serious or fatal injury in three different countries. Further research on PTW rider injuries in detail as a function of these configurations would complement this study. Studies using data from other countries where a high proportion of PTW fatalities would be helpful in revising the ISO 13232 standard. Besides, this study might be useful as the first step towards the development of appropriate protective equipment for PTWs, which could be evaluated by means of virtual tests using human body models or full-scale physical tests. An updated version of the ISO standard may serve as a basis for a full-scale PTW test program.

5. Conclusion

The most frequent crash configurations in which a PTW rider was fatally or seriously injured were: (a) PTW front impacting front or side of passenger car, (b) PTW front impacting front or side of truck, and (c) PTW impacting ground (primary collision). The ISO 13232 specifies crash configurations which do not accurately represent the most frequent crashes in Germany and India, or the crashes described in CIDAS. We observed distinct differences in the most common crash configurations between databases, including higher speeds in GIDAS. However, due to the observed differences, a global standard with a single set of crash configurations might not be feasible. Therefore, we recommend the adoption of two sets of crash configurations: a global set, representative of frequent crashes around the world, and a more customized set, representing crashes that are frequent in the specific region for which the PTW safety systems are to be evaluated.

CRediT authorship contribution statement

Pradeep Puthan: Conceptualization, Methodology, Formal analysis, Data curation, Writing - original draft, Writing - review & editing, Visualization. **Nils Lubbe:** Conceptualization, Methodology, Writing - review & editing, Resources, Supervision. **Junaid Shaikh:** Data curation. **Bo Sui:** Data curation. **Johan Davidsson:** Methodology, Writing - review & editing, Supervision.

Declaration of Competing Interest

The authors report no declarations of interest.

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Appendix A. GIDAS weighting

In the selected data for the analysis, there were 17 cases with both L1e and L3e classes. In those cases, the weight of L3e was selected because this category is more relevant for this study. All the frequencies and weights are given below (Table A1). An example calculation is given below for the L1e class fatal crashes in GIDAS.

$$\text{Weight} = \frac{Frequency_{GIDAS}}{Frequency Destatis} = \frac{60}{14} = 4.29$$

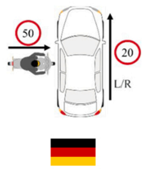
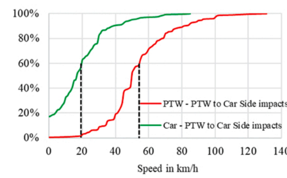
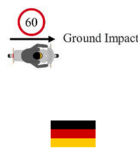
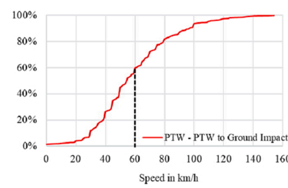
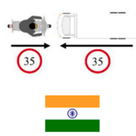
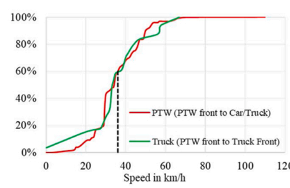
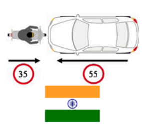
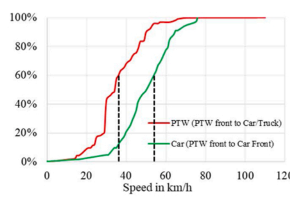
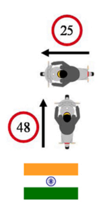
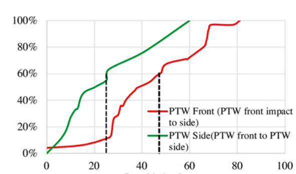
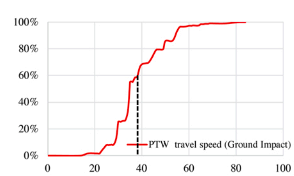
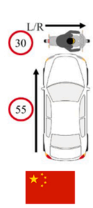
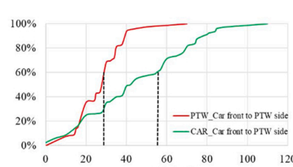
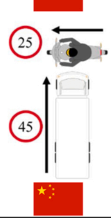
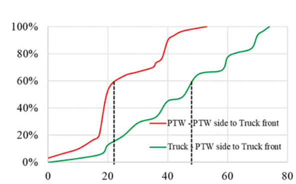
Table A1
Weighting factors.

	Severity	DESTATIS Freq.	GIDAS Freq.	Weights
L1e Class	Fatal	60	14	4.29
	Serious	2,842	518	5.49
	Slight	10,848	1,262	8.60
L3e Class				
	Fatal	585	113	5.18
	Serious	9,544	1,303	7.32
	Slight	17,991	1,831	9.83

Appendix B. Cumulative distribution of travel speeds

See Table B1.

Table B1
Distribution of travel speeds in the most frequent crash configurations.

Most frequent crash configuration	Cumulative distribution of travel speeds of collision partners
	
	
	
	
	
	
	
	

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